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AN EVALUATION OF LOW COST SOLID-STATE ACCELEROMETERS

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ABSTRACT

Semiconductor technology enables solid state accelerometers to be mass produced for less than $100 in the ranges required for most automotive crash testing applications. The purpose of this study was to evaluate these low cost accelerometers and determine if they can be used to accurately measure dynamic responses in impact tests. Replacement of conventional manually constructed accelerometers with solid state transducers would result in a significant savings.

Solid state accelerometers from two manufacturers were compared with more expensive ($400-$700) conventional accelerometers. The accelerometers were calibrated to obtain their output sensitivity, drop tested to determine if they had a linear output over their specified range, and were compared with conventional accelerometers in actual impact tests.

Preliminary testing of the solid state accelerometers indicate the output responses compare well with conventional accelerometers. The sensitivity of the solid state transducer, although less than a conventional accelerometer of the same range, provided a sufficient output signal. The accelerometers were linear well beyond their rated range and their outputs compared well with conventional accelerometers over a wide range of impact tests. The accelerometer outputs are stable and exhibit very little zero drift. They are small, rugged, and able to withstand accelerations up to 2000 g's without damage.

An Evaluation of Low Cost Solid-State Accelerometers

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Purpose

The purpose of this study was to evaluate low cost solid state accelerometers and determine if they can be used to measure accurately dynamic responses in crash tests.

Introduction

A Hybrid III Anthropomorphic Dummy contains a minimum of six to as many as 25 accelerometers for measuring accelerations and for kinematic analysis of angular and linear velocities and displacements. Conventional accelerometers cost between $400 and $700, resulting in an investment of about $12,500 per dummy. Accelerometers are frequently used to obtain additional information about the test environment such as sled acceleration and velocity, or impactor applied force. Accelerometers are typically small in size, light in weight, and can be used to monitor not only acceleration but, velocity when integrated, and displacement when double integrated. Because accelerometer measurements are so useful to the test engineer, they are often used in places that could destroy them during testing. These potentially destructive locations provide an ideal place for the use of a low cost solid state accelerometer.

Semiconductor technology enables solid state accelerometers to be mass produced for less than $100 in the ranges required for most automotive crash testing applications. The solid state accelerometer consists of a micro-machined silicone mass suspended by multiple beams to a silicone frame, the top and bottom of the frame is covered by silicone wafers which act as over range stops. Piezoresistive elements located on the beams are connected into a fully active 4 arm Wheatstone bridge. These elements change resistance as the mass moves relative to the frame resulting in an electrical output proportional to the applied mechanical acceleration.

Two sources of solid state accelerometers were tested:

1. IC Sensor, 1701 McCarthy Blvd. Milpitas, California 95035
   Phone (408) 432-1800

2. Sensym, 1255 Reamwood Ave. Sunnyvale, California 94089
   Phone (408) 744-1500

Solid state accelerometers are presently available in eight ranges from $\pm 2g$ to $\pm 500g$ and in several packaging configurations. A small 0.3" x 0.3" x 0.14" surface mount version is available as well as a

1.374" x 0.6" x 0.185" accelerometer with mounting brackets. All of the solid state accelerometers we tested required the use of contact cement for mounting.

Evaluation

The first step in the evaluation of the solid-state accelerometers was to determine the sensitivity and linearity of each device. They were then compared with Endevco Model 7264-2000 and Model 7231C-750 accelerometers under normal test conditions. The Endevco accelerometers are commonly used to measure dynamic responses in automotive crash testing.

The criteria used to determine the effectiveness of the solid state accelerometers follows:

1. Linearity: Provide a linear output over the useful specified range of the accelerometer .

2. Sensitivity: Provide a sufficient signal-to noise output signal at the acceleration range selected.

3. Frequency Response: Have a mounted resonant frequency much higher than the expected frequency to be recorded.

4. Cross Axis Sensitivity: Be insensitive to transverse or off-axis accelerations.

5. Low Mass: Accelerometers must be small and light weight so as not to influence the responses of the device being monitored.

6. Ruggedness: The accelerometer must withstand the severe environment of impact testing, in terms of potentially sharp, high amplitude acceleration spikes.

7. Thermal Stability: Exhibit minimal output shift due to temperature variations.

Calibration

The method used to verify the accuracy and linearity of the solid state accelerometers was to calibrate them using sinusoidal motion excitation. This employs an electro-dynamic shaker that vibrates a reference and test accelerometer at a known level. The sensitivity of the test transducer was determined by comparing its output to the reference accelerometer. The reference accelerometer was an Endevco Model 2270 calibrated by the manufacturer for use as a standard in comparison calibration.

The test accelerometer was mounted on top of the reference accelerometer and vibrated by a Unholtz-Dickie Electro-Dynamic shaker (Figure 1.). The amplitude and frequency of the sinusoidal vibration were determined by the signal generator and driver amplifier which were set to obtain 100 Hz at an amplitude of 10 g's. The test accelerometer output was conditioned (provided regulated 10 Volts D.C. excitation and balanced), amplified and compared to the reference transducer. The reference accelerometer has an output of exactly 1 mv/g (Endevco Model 2270) which was amplified by the Model N441 Standard amplifier. The output of the N441 is applied to the Model N440 Sensitivity Computer Module which contains a decade voltage divider circuit that adjusts the standard output equal to the test signal. When the amplitudes of the test and reference accelerometers are equal, as determined by the Model N418 Null Meter, the sensitivity of the test transducer is displayed by the settings of the decade switches on the Sensitivity Computer.

Solid-state accelerometers are full bridge piezo-resistive devices and therefore, can be calibrated by shunt resistance substitution across one leg of the bridge (Figure 2.). A shunt resistor calibration value can be determined by monitoring the output of the test accelerometer on a voltmeter, applying a variable resistance across the bridge and adjusting the resistance until the desired output is obtained. The formula used to determine the output is:

OUTPUT = SENSITIVITY X RANGE X GAIN

where:

SENSITIVITY = Sensitivity of the test accelerometer as determined by the Sensitivity Computer.

RANGE = The desired calibration unit, for example 100 g's.

GAIN = The gain of the amplifier used as the test amplifier.

Table 1 provides examples of the measured sensitivity vs the factory specified sensitivity, using 10 volts D.C. excitation and a 50g equivalent shunt calibration resistance value.

Table 1.

ACCELEROMETER SENSITIVITY

MFG	MODEL	S/N	FACTORY mv/g	MEASURED mv/g	50g Equiv. Resistance
ENDEVCO	7231C	FL36	0.2104	0.2110	116.8k
ENDEVCO	7231C	FL39	0.2353	0.2353	104.8k
ENDEVCO	7231C	FL40	0.2295	0.2310	107.3k
ENDEVCO	7231C	FL29	0.2252	0.226	113.3k
SENSYM	SXL200G	005	N.A.	0.4250	643.0k
SENSYM	SXL200G	006	N.A.	0.3320	731.0k
SENSYM	SXL200G	007	N.A.	0.3660	717.0k
IC SENS	3021-500	3A11253	0.1580	0.1540	930.0k
IC SENS	3021-500	3A11258	0.164	0.157	885.8k
IC SENS	3021-500	3A11259	0.142	0.136	1027.2k

Cross Axis Sensitivity

The cross axis sensitivity of solid state accelerometers was compared with an Endevco 7264-2000T accelerometer. The T option of this particular accelerometer specifies a maximum traverse sensitivity of 1 %. The electro-dynamic shaker was again used as the test device for comparison. The 7264-2000T and the solid state accelerometers were placed on opposite sides of a block, mounted with the sensitive axis of each accelerometer 90 degrees from the direction of vibration. The shaker reference accelerometer was used to monitor the amplitude and frequency of the axial input vibration.

The shaker head is not constrained so there is some lateral motion during operation, the lateral amplitude varies as the frequency of vibration is changed. The shaker was initially adjusted to obtain an output on the reference accelerometer of approximately 50 g's peak-to-peak and while monitoring the output of the Endevco accelerometer, adjusted the frequency to obtain minimum lateral motion. The output of each accelerometer is shown in Figure 3, the bottom plot is the reference accelerometer, the top plot displays the Endevco 7264-2000T as a solid-line curve and the Sensym SXL200G as a dashed-line curve. The outputs of these accelerometers are almost identical. The frequency of the shaker was then swept from 100 Hz to 2500 Hz and the output responses tracked well. This procedure was repeated with several different solid state accelerometers and they all compared well with the Endevco.

Drop Testing

The next stage in evaluation employed the Endevco Model 2965C Shock Calibrator. The Shock Calibrator provides accelerations at higher g levels than the shaker therefore, a check of the output linearity of the test accelerometer over a wide range. This calibration method uses various size steel balls dropped onto a mass (anvil) held in place by permanent magnets. The reference and test accelerometers are attached to the mid point of the anvil opposite the site of impact. The top side of the anvil is padded with a thin rubber bumper, the heavier the anvil the thicker the bumper.

When the ball is dropped it strikes the anvil which breaks away from the magnet and falls freely until stopped by a cushion at the bottom of the calibrator. The dropped ball is arrested shortly after impact by a rubber ring inside the calibrator. During impact the same acceleration is applied to both transducers. The amplitude and duration of acceleration can be varied by using different ball and anvil combinations.

The output from the test and reference accelerometers are sampled by the data acquisition system at 50,000 samples/second/channel. The output peak levels and the percentage of full scale output error are recorded in Table 2.

Table 2

ACCELEROMETER DROP TEST RESULTS

ACC #	TYPE	RANGE	TEST PEAK G	REF PEAK G	FSO %
1	SENSYM	200g	-25.66	-25.32	0.17
1	SENSYM	200g	-26.38	-25.93	0.22
1	SENSYM	200g	-66.81	-66.30	0.26
1	SENSYM	200g	-64.15	-63.75	0.20
1	SENSYM	200g	-109.66	-110.17	-0.26
1	SENSYM	200g	-109.17	-110.17	-0.50
1	SENSYM	200g	-165.88	-163.78	1.05
1	SENSYM	200g	-147.90	-148.20	-0.15
1	SENSYM	200g	-293.08	-288.94	2.07
1	SENSYM	200g	-303.27	-299.96	1.66
1	SENSYM	200g	-434.79	-429.67	2.56
1	SENSYM	200g	-473.62	-472.13	0.75
5	IC SENS	200g	-25.28	-25.32	0.08
5	IC SENS	200g	-26.25	-26.09	0.08
5	IC SENS	200g	-64.23	-63.54	0.35
5	IC SENS	200g	-67.12	-66.07	0.53
5	IC SENS	200g	-111.59	-110.83	0.38
5	IC SENS	200g	-110.39	-110.83	-0.22
5	IC SENS	200g	-164.48	-162.48	1.00
5	IC SENS	200g	-159.79	-158.15	0.82
5	IC SENS	200g	-392.53	-394.29	-0.88
5	IC SENS	200g	-397.94	-395.50	1.22
5	IC SENS	200g	-570.59	-570.69	-0.05
5	IC SENS	200g	-564.16	-568.30	-2.07

Comparison Testing

Comparison measurements using both solid-state and conventional accelerometers were made under real test conditions. The backcap of the head of a Hybrid III Dummy contains five Endevco Model 7264-2000 accelerometers. These (inline) accelerometers are used to compute 2D angular motions, this approach requires a high degree of accuracy to provide a reliable solution in the computation. The inline accelerometers are aligned in the longitudinal plane and measure linear acceleration. As the head rotates about the Y axis each device measures a different acceleration, and with precise mounting separation of the accelerometers, these differences can be used to compute angular motion. Figure 4a. shows the acceleration time history of test 1704 and Figure 4b. shows test number 1705, in which Endevco Model 7264-2000 accelerometers were installed in all five inline positions. In tests 1827 (Figure 4c.) and 1828 (Figure 4d.) two of these accelerometers were replaced by solid-state transducers. Similar results were obtained when using the solid state accelerometers.

A Model 3031 500g IC Sensor accelerometer was mounted on the front of a 23.4 kg pneumatically assisted power pendulum. The power pendulum is propelled by an air driven piston up to a velocity of 15 m/s in less than 150 mm of travel. The power pendulum is used as a high speed impact device to calibrate dummy components and to evaluate the performance of other parts during impact. Figure 5(a) shows the raw data from an Endevco 7231C-750 accelerometer (solid line) and a IC Sensor 3031-500 accelerometer (dashed line) overplotted on the same grid for typical pendulum impact tests. In Figure 5(b) the same data is plotted after filtering with a SAE Class 180 filter. The pendulum accelerometer output is normally filtered and multiplied by the pendulum mass to obtain the force applied to the target. The data obtained from this computation was similar using either accelerometer over a large number of tests.

Figure 6 compares the output of a Statham Model A69TC-250-350 accelerometer with a Sensym Model SXL200G accelerometer used to measure sled acceleration, raw data as well as data filtered at SEA Class 60 is displayed. The velocity of the Hyge Sled, installed in the Research Labs

Biomedical Science Department, is determined by integrating the output of the sled accelerometer. Table 3 lists the peak outputs from 12 successive Sled tests. Column 1 lists the peak Statham acceleration, in column 2 the peak velocity obtained from integrating the Statham accelerometer in meters/second is shown. Column 3 contains the Sensym peak acceleration, and column 4 has its corresponding velocity listed. In column 5 the percent difference of the peak acceleration for each test is listed, and column 6 contains the percentage difference of the peak velocity. The average difference for these 12 tests was 0.22 % for peak acceleration and 0.17 % for peak velocity. The Sensym accelerometer has been used for over 50 sled tests and the measured velocity compared well with the Statham transducer.

Table 3

Statham vs Sensym Sled Measurements

STATHAM ACC g	STATHAM VEL m/s	SENSYM ACC g	SENSYM VEL m/s	ACC DIFF %	VEL DIFF %
26.73	15.01	26.92	15.19	0.71	1.18
26.68	14.99	26.6	15.09	-0.30	0.66
26.78	14.92	27.12	15.06	1.25	0.93
26.76	15.02	26.97	15.16	0.78	0.92
26.48	15.02	26.47	14.99	-0.04	-0.20
27.01	15.09	27.09	15.02	0.30	-0.47
26.80	15.04	26.92	15.14	0.45	0.66
26.77	15.03	26.76	15.03	-0.04	0.00
26.63	15.09	26.80	15.16	0.63	0.46
26.94	15.12	26.77	15.13	-0.64	0.07
26.90	14.99	26.92	14.79	0.07	-1.35
25.38	14.46	25.22	14.33	-0.63	-0.91

The most severe test of an accelerometer in this facility occurs during a dummy head impact into a windshield. Under most conditions the head vibrates and in some cases the accelerometers go into oscillation at its natural frequency. It is important that this frequency be high enough that it can be filtered out and not distort the desired lower frequency content. Figures 7 through 9 demonstrate the triaxial accelerometer responses of a Hybrid III head, dropped in freefall from a height of two meters, onto a supported automotive windshield. In Figures 7a, 8a, and 9a, the bottom traces show an Endevco 7231C-750 Accelerometer unfiltered data sampled at 20,000 samples/second/channel, the middle curves are the same data filtered at 1000 Hz, and the top traces are a frequency vs power spectrum of the raw data. Figures 7b, 8b, and 9b, demonstrate the same impact using Sensym SXL200G accelerometers mounted in parallel with the conventional accelerometers on the head tri-axial mounting block. The Fourier transform (FFT) of the unfiltered data shows most of the energy of the impact occurred below 1000 Hz with some oscillation between 4 kHz and 8 kHz, the higher frequencies occurred mainly in the lateral and vertical directions. It is apparent from the filtered data that the high frequencies can be removed without distorting the signals of interest. When any transducer oscillates care must be taken not to saturate the conditioning amplifier which can result in low frequency signal distortion.

Conclusions

1) Solid state accelerometers have been tested in different and sometimes extreme environments. A 500g IC Sensor accelerometer was installed on our pneumatically powered pendulum. It operated reliably and accurately compared with a conventional accelerometer in a large

number of impact tests. A 200g Sensym and a 500g IC Sensor accelerometer were used to measure test dummy head angular motion during sled impact tests. A single 200g Sensym was used to measure sled acceleration. In all cases these solid state accelerometers were mounted in parallel with more expensive conventional accelerometers and compared well in output response.

2) In drop tests that compared the output to a standard accelerometer, the solid state transducers were linear well beyond their rated range.

3) The sensitivity of the solid state accelerometer, although less than a conventional accelerometer of the same range, provided a sufficient signal-to-noise output over the full range of the transducer. Once nulled and calibrated, the solid state accelerometer is stable and exhibits very little zero drift. These accelerometers are small, rugged, and are able to withstand accelerations up to 2000 g's without damage.

Summary

The Solid-state accelerometers which were tested performed well and the output data were comparable to more expensive conventionally constructed accelerometers. The accelerometers tested are stable and exhibited very little zero drift after balancing and calibration. The sensitivity of these solid state accelerometers is high enough to provide a good signal-to-noise output. The cross axis sensitivity of the solid state accelerometers compared with an Endevco accelerometer specifically selected for its low traverse axis sensitivity. They are small in size, light in weight, and rugged enough to withstand accelerations up to 2000 g's without failing. All of the solid state accelerometers survived testing and remain operational.

The Solid-state accelerometers we tested were packaged on a ceramic substrate and mounted using contact cement. Other packages that include mounting brackets are available from the manufacturer. The accelerometers vary in size from 0.3" x 0.3" x 0.14" for the IC Sensor Model 3031 to 1.374" x 0.6" x 0.14" for the IC Sensor Model 3026 with mounting hardware.

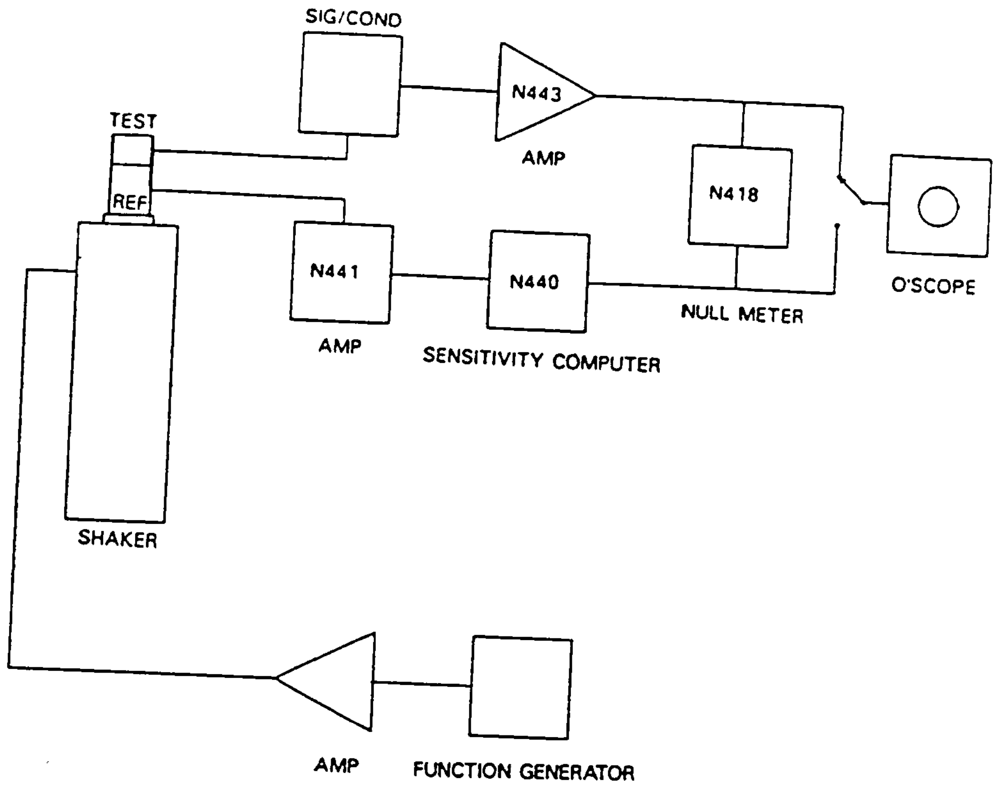

Figure 1. Calibration Block Diagram.

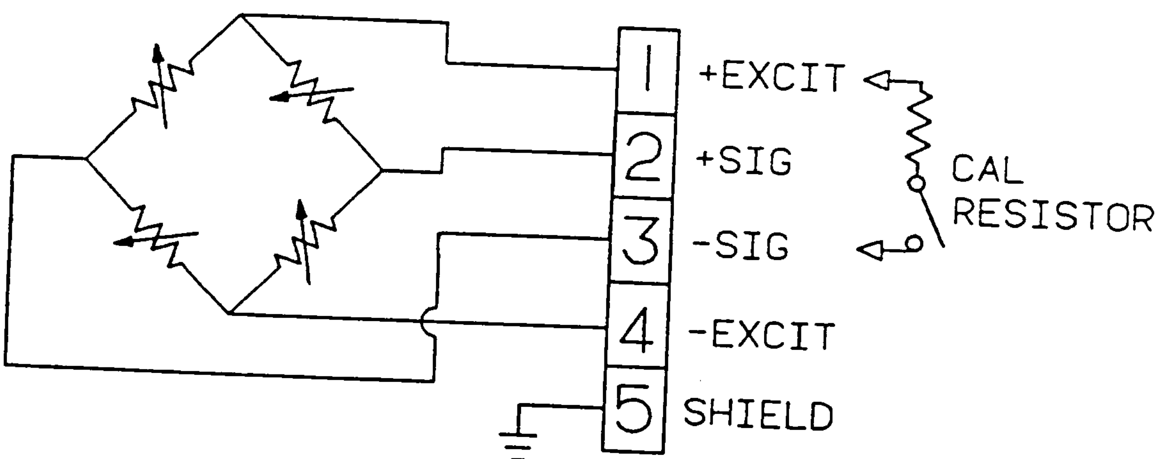

Figure 2. Accelerometer Wiring Diagram.

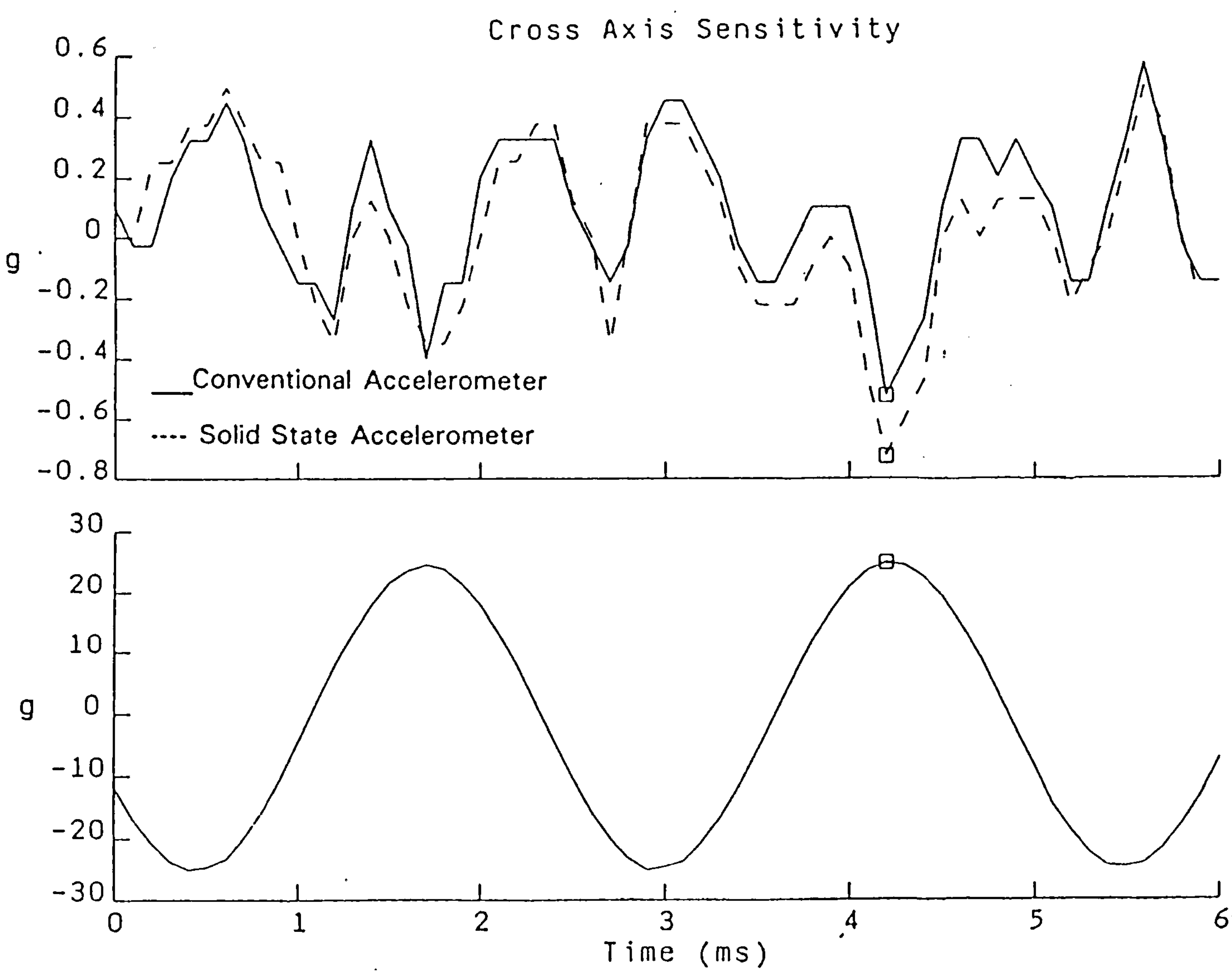

Figure 3. Cross axis sensitivity, conventional vs solid state accelerometers.

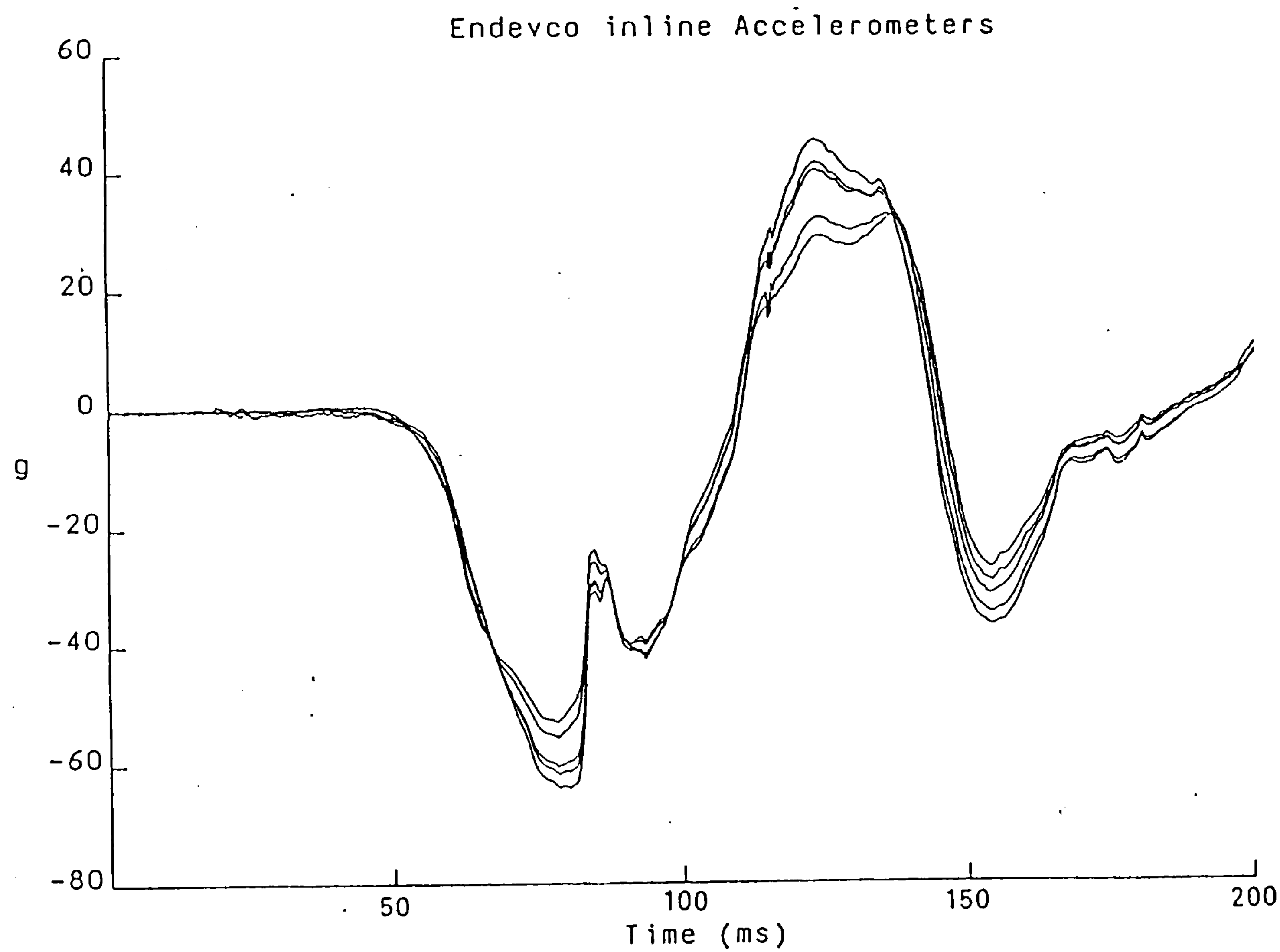

Figure 4a. Five conventional inline accelerometers in backcap.

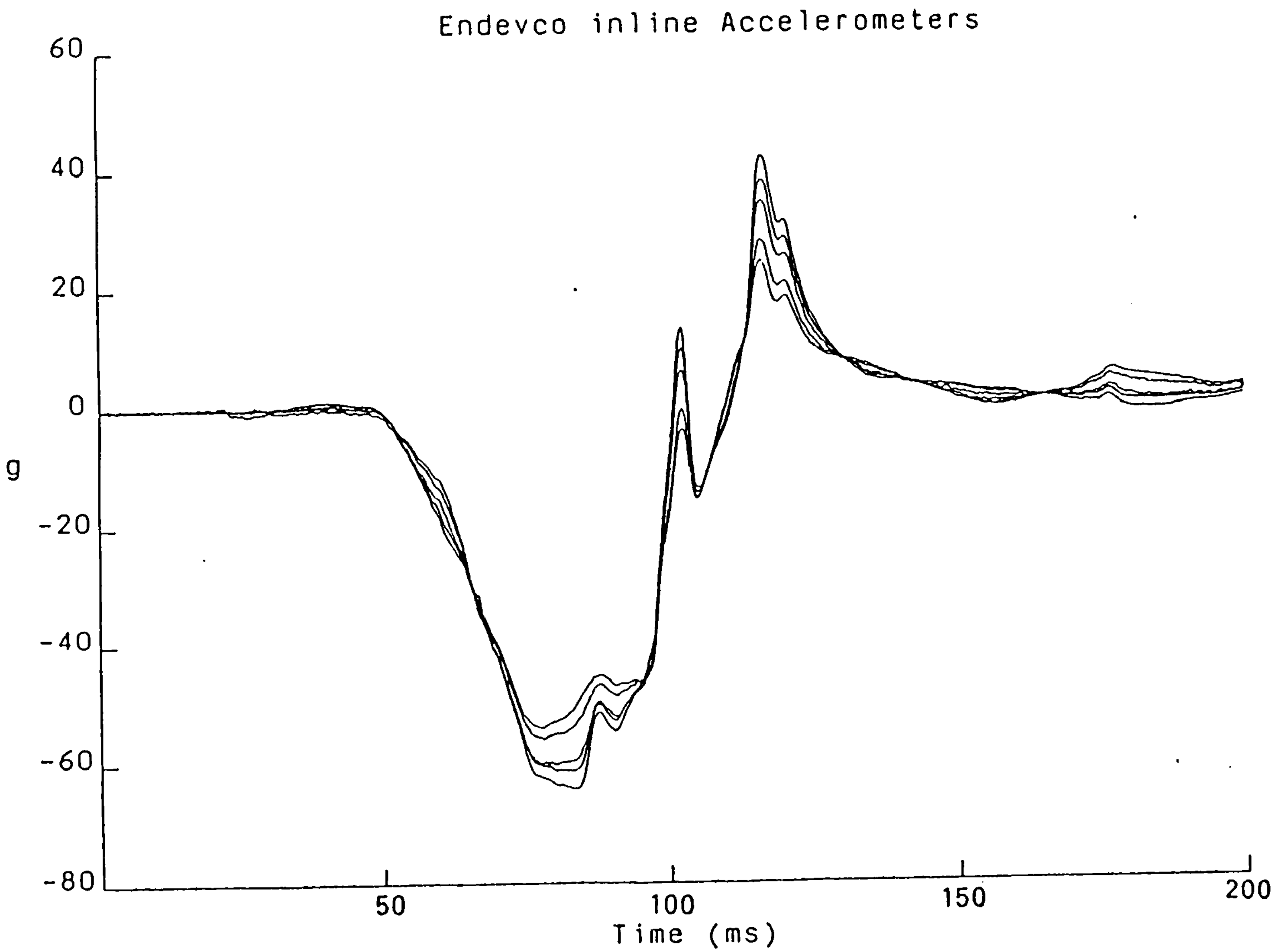

Figure 4b. Five conventional inline accelerometers.

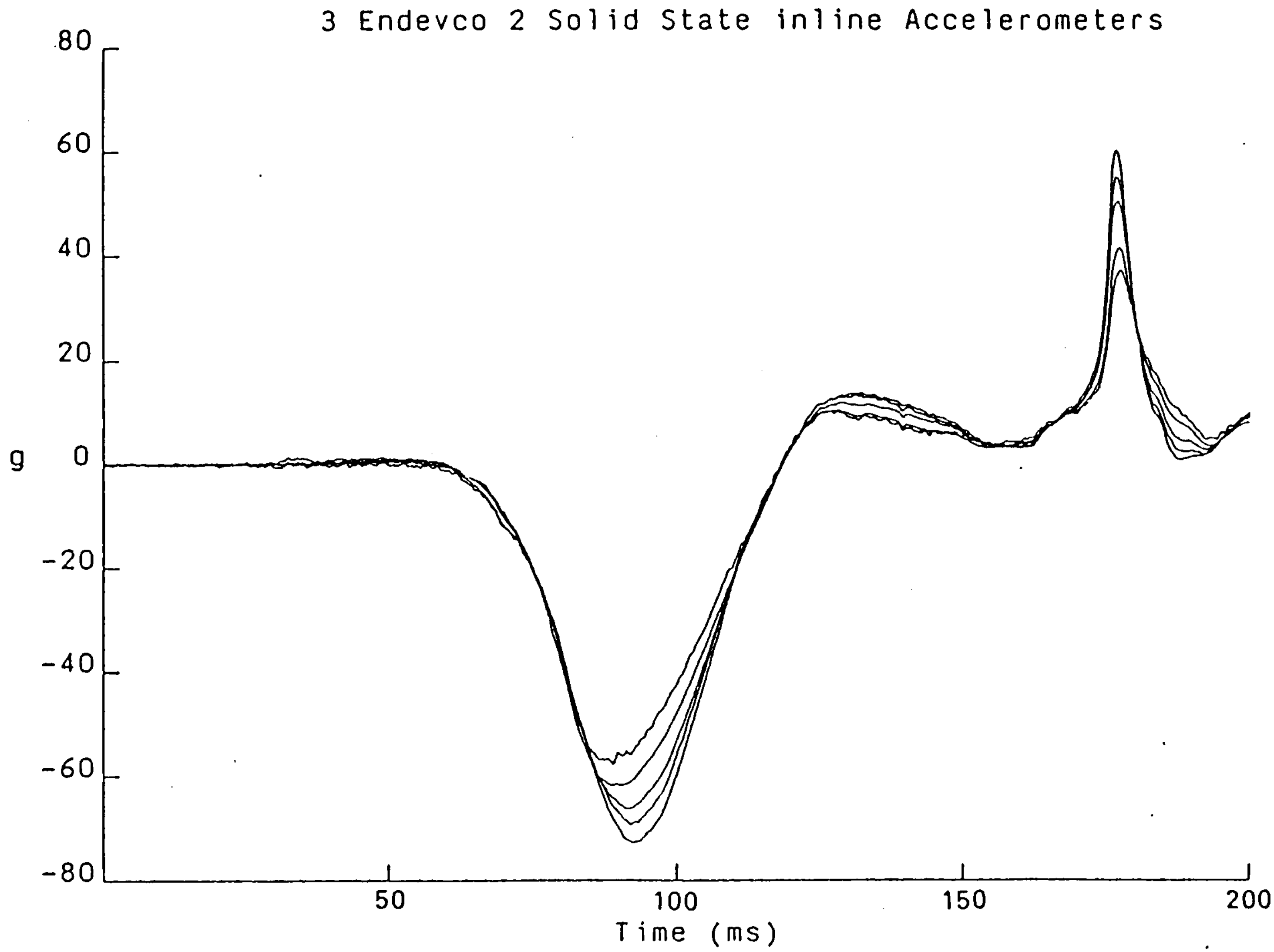

Figure 4c. Three conventional, two solid state inline accelerometers.

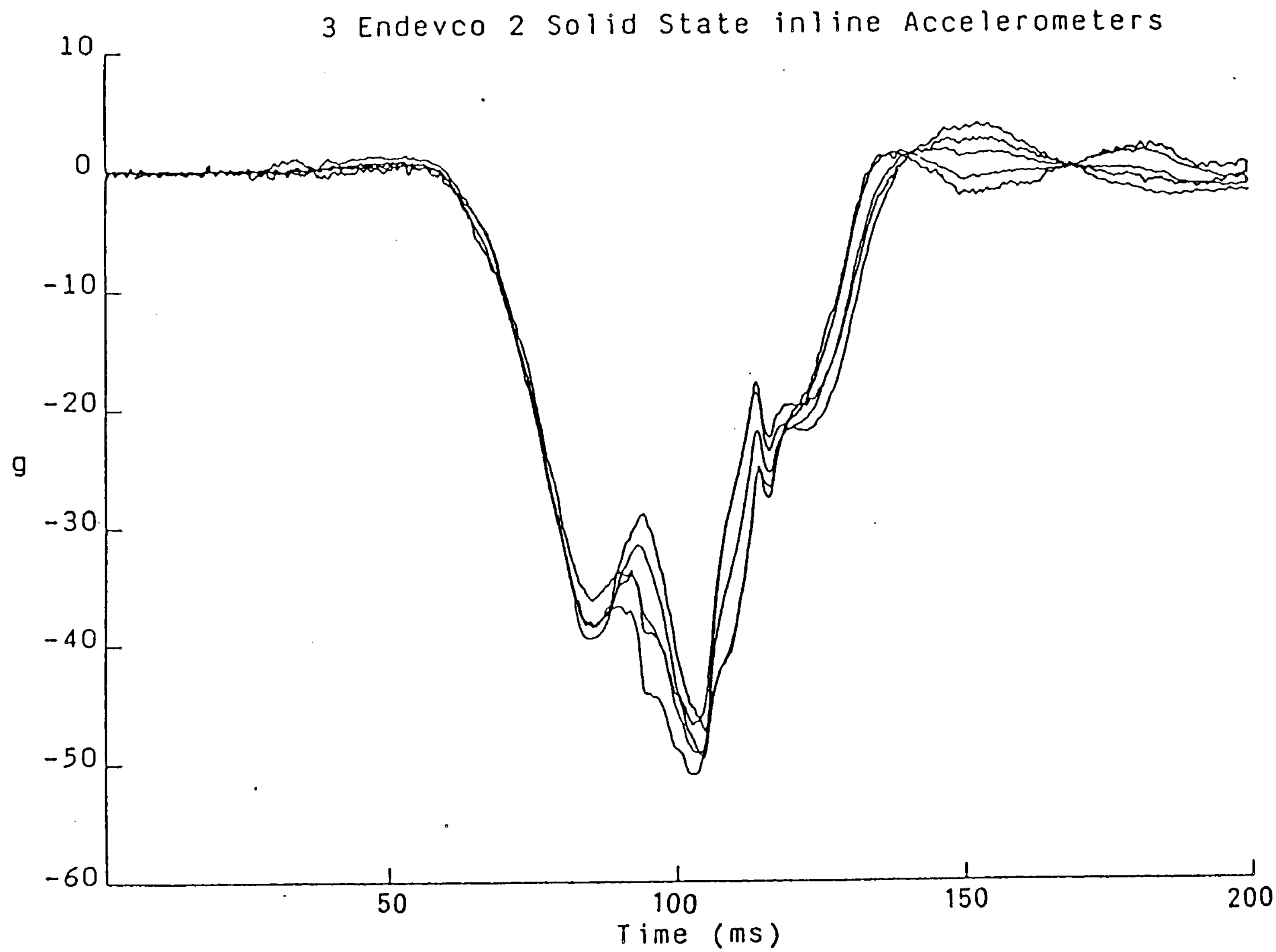

Figure 4d. Three conventional, two solid state inline accelerometers.

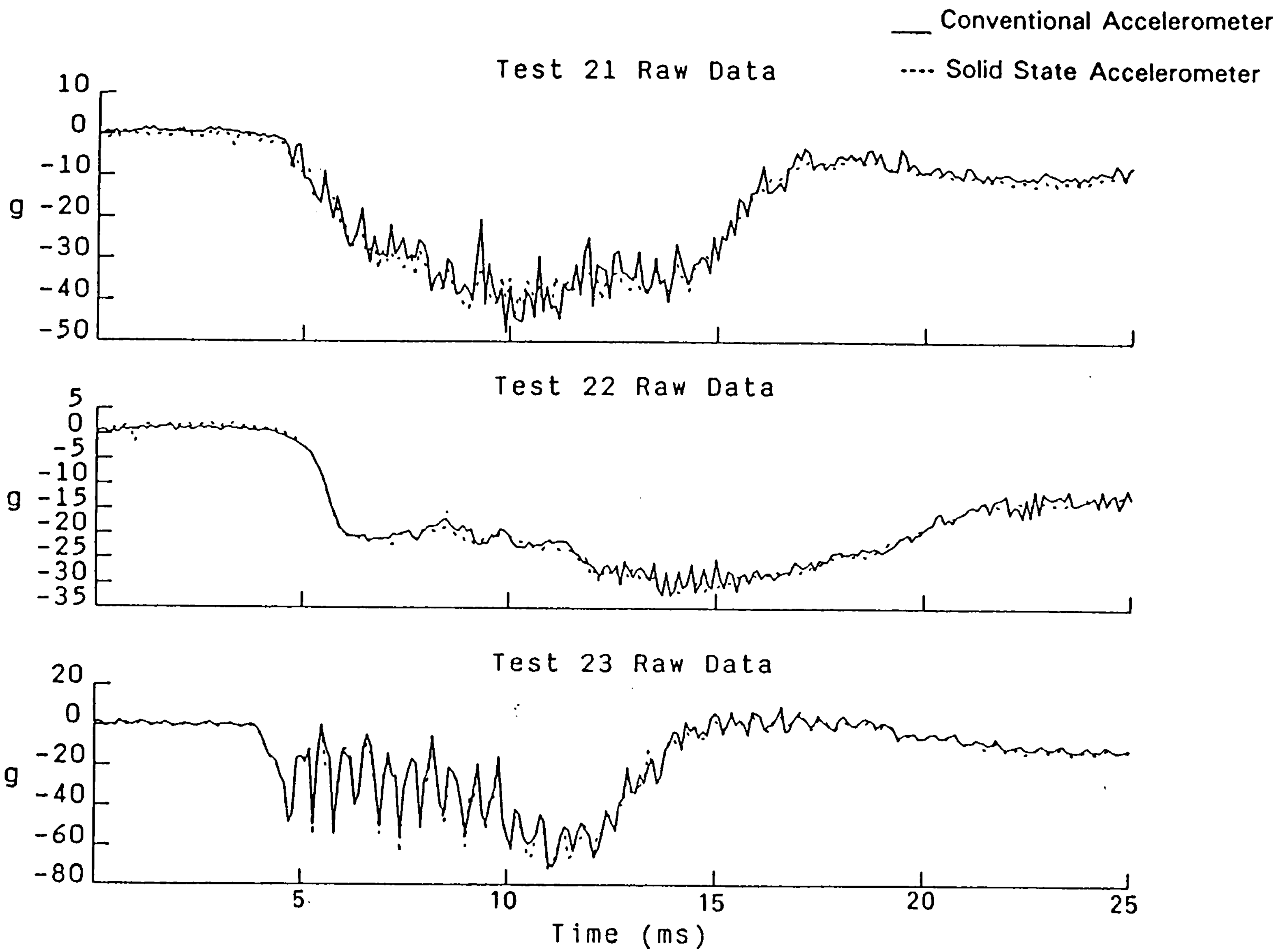

Figure 5a. Unfiltered pendulum acceleration, conventional vs solid state.

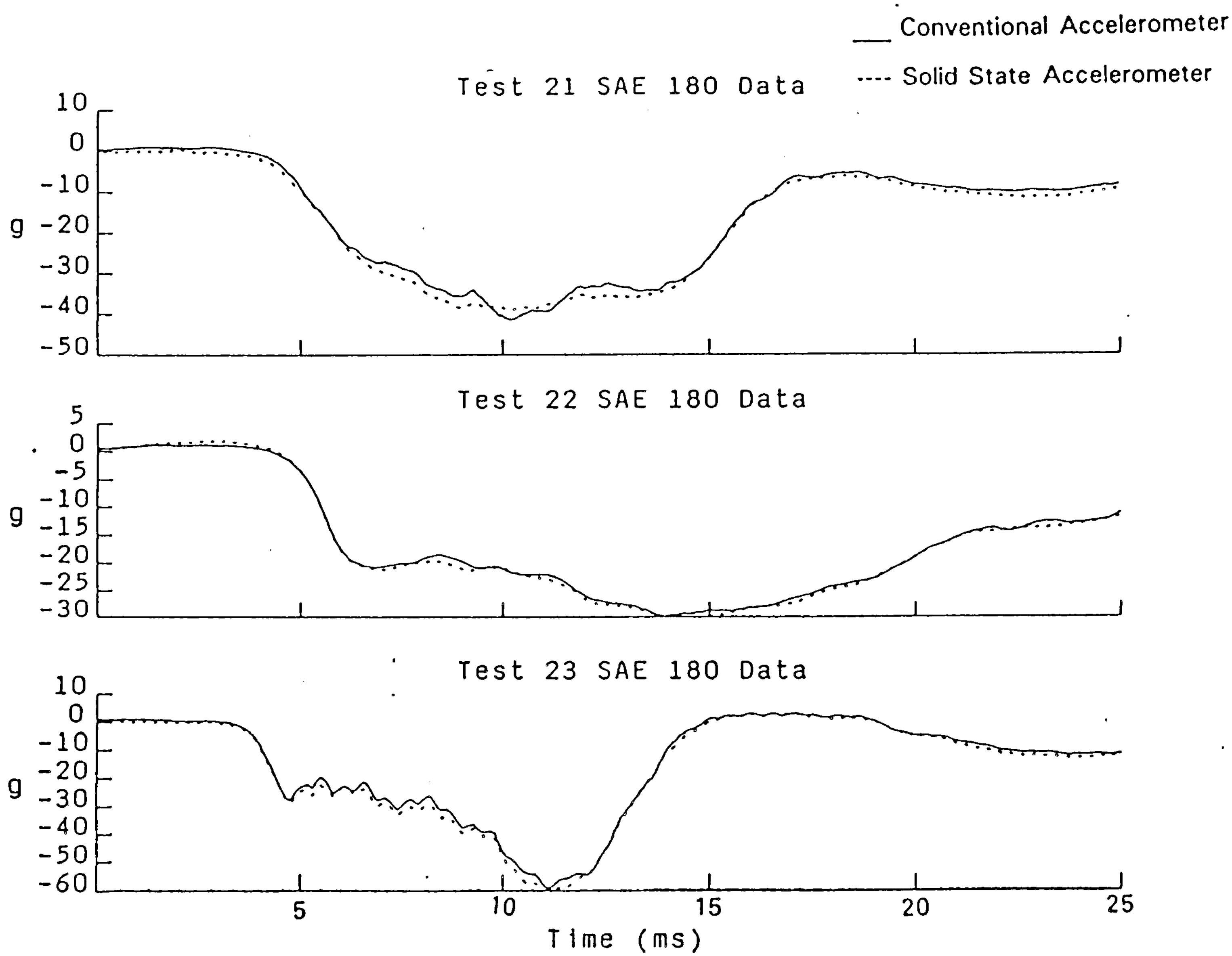

Figure 5b. SAE 180 pendulum acceleration, conventional vs solid state.

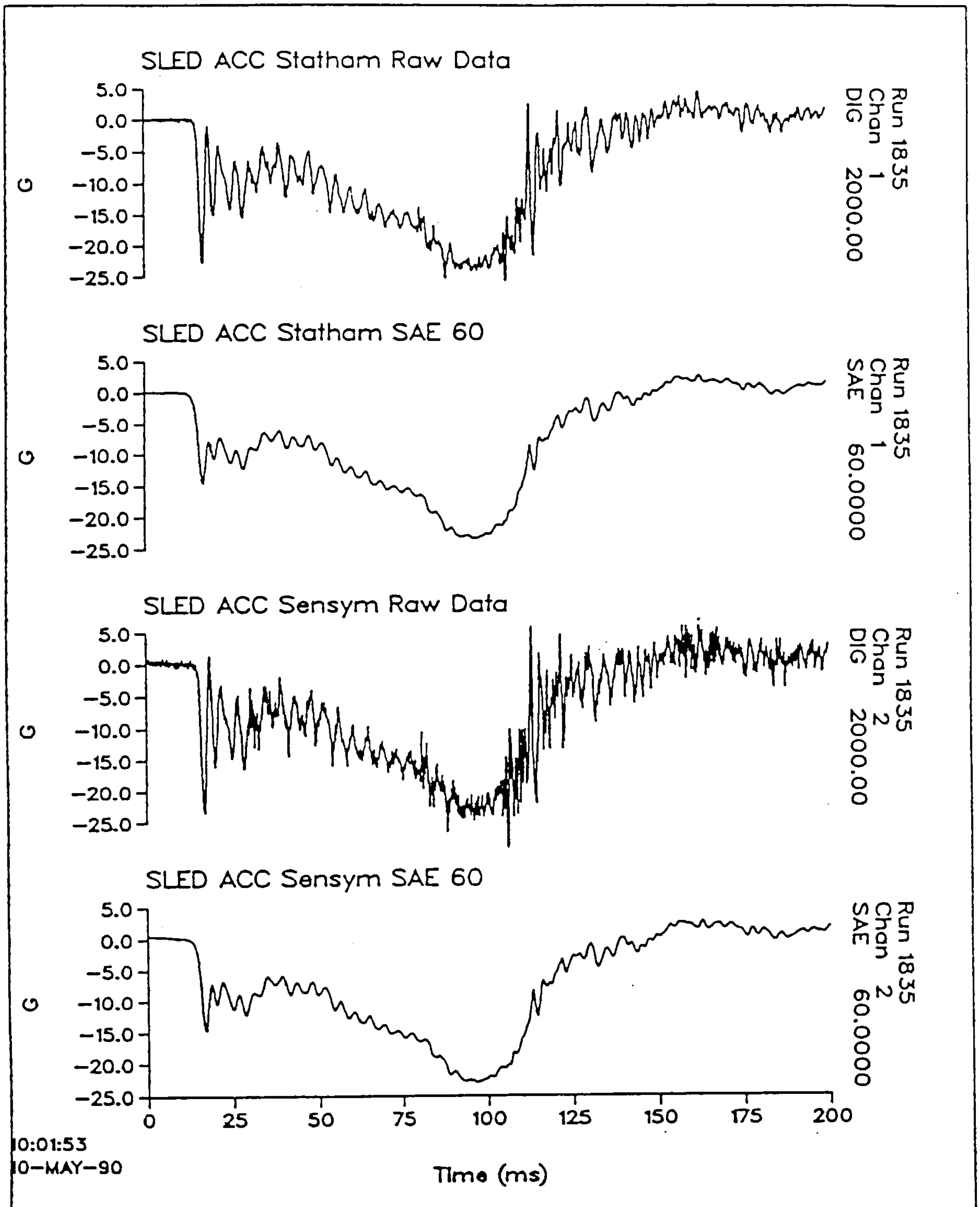

Figure 6. Conventional and solid state sled acceleration responses.

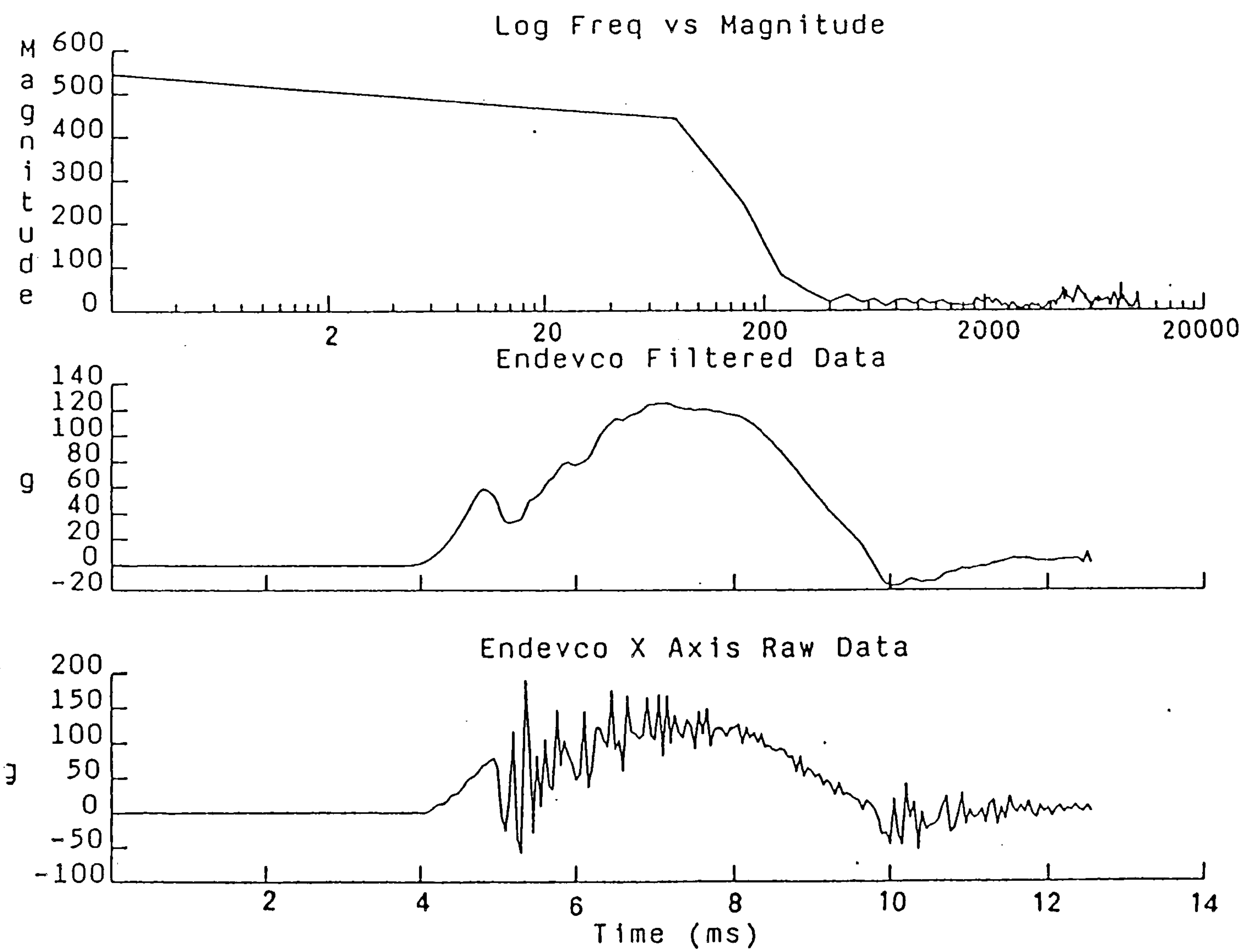

Figure 7a. Glass impact, conventional accelerometer response.

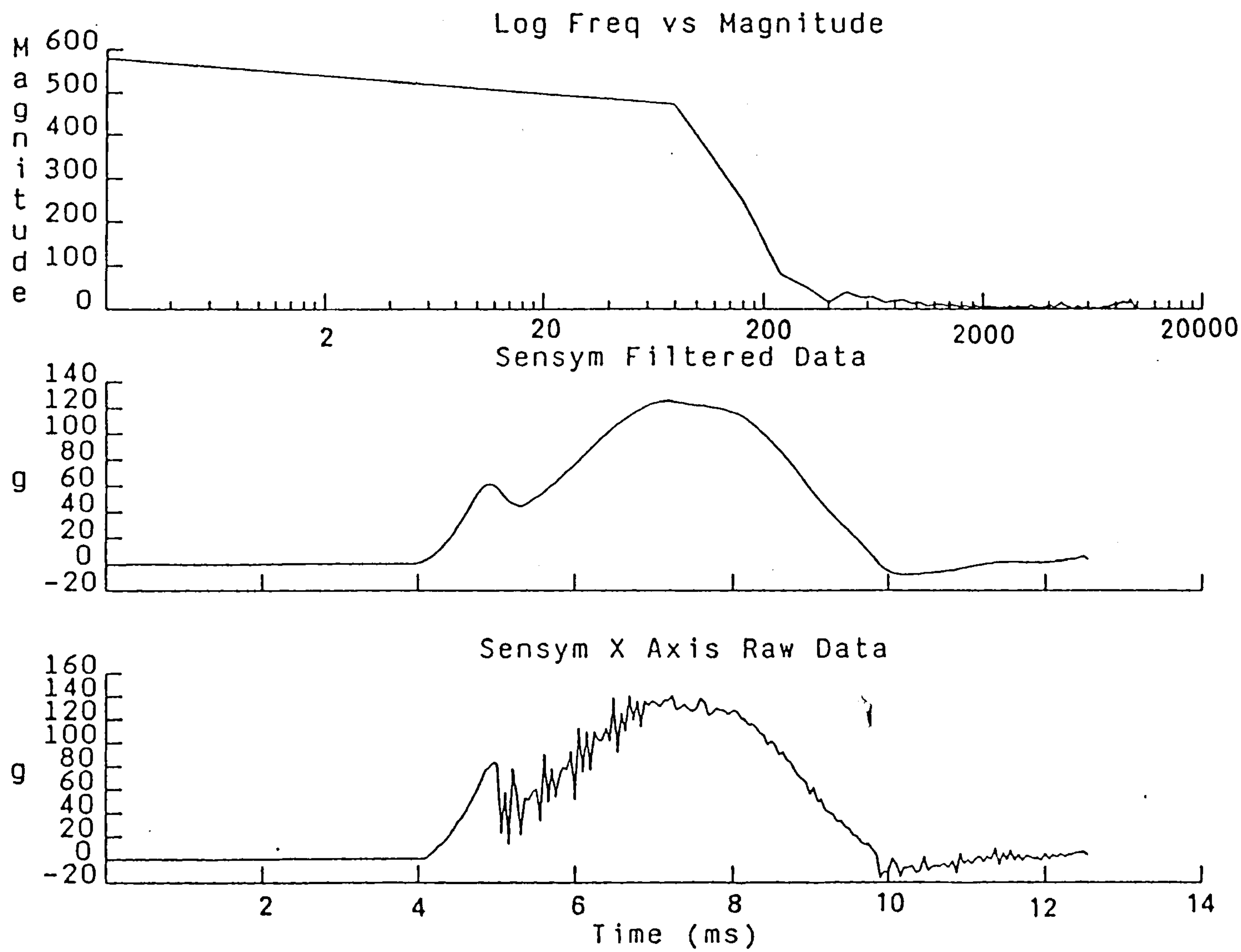

Figure 7b. Glass impact, solid state accelerometer response.

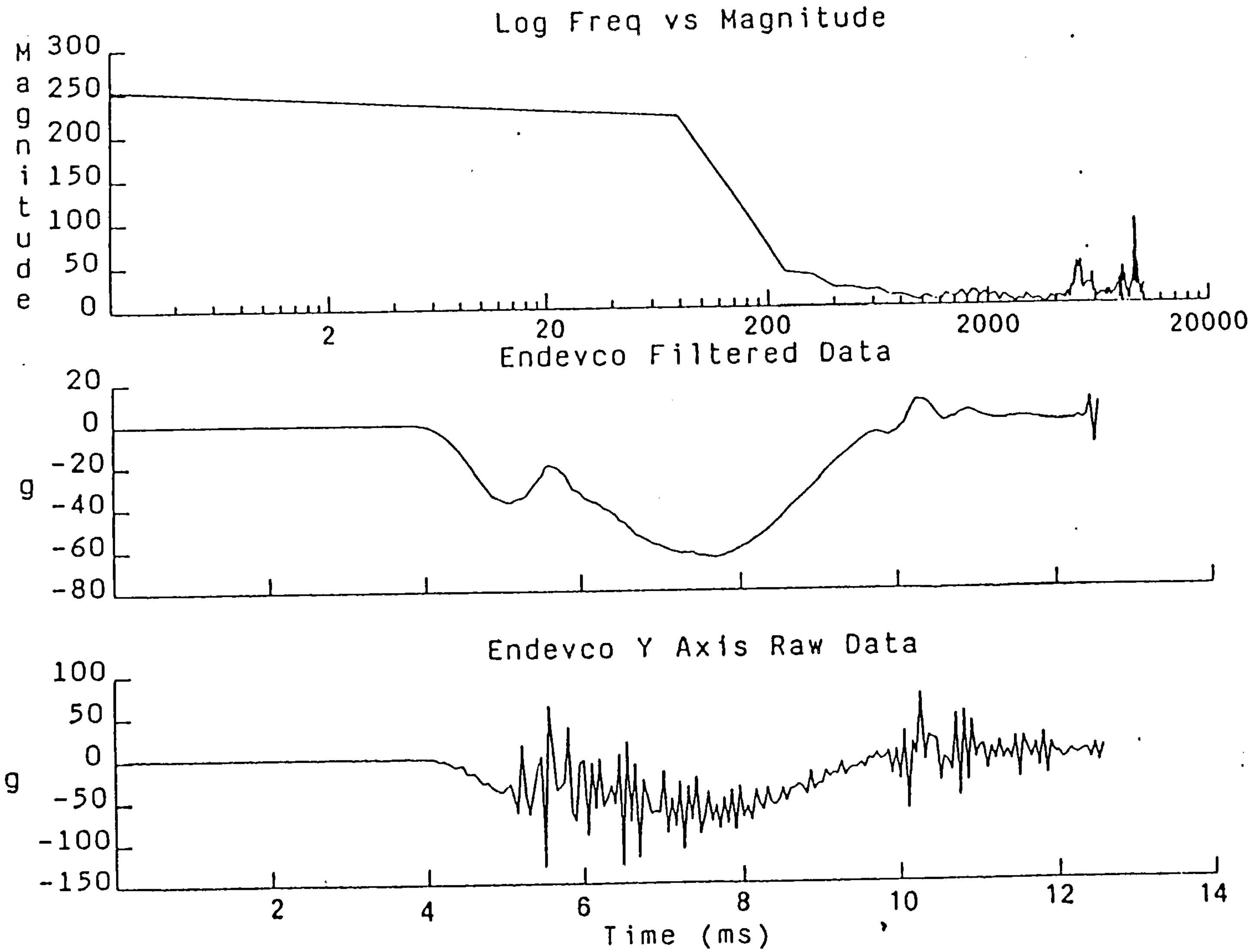

Figure 8a. Glass impact, conventional accelerometer response.

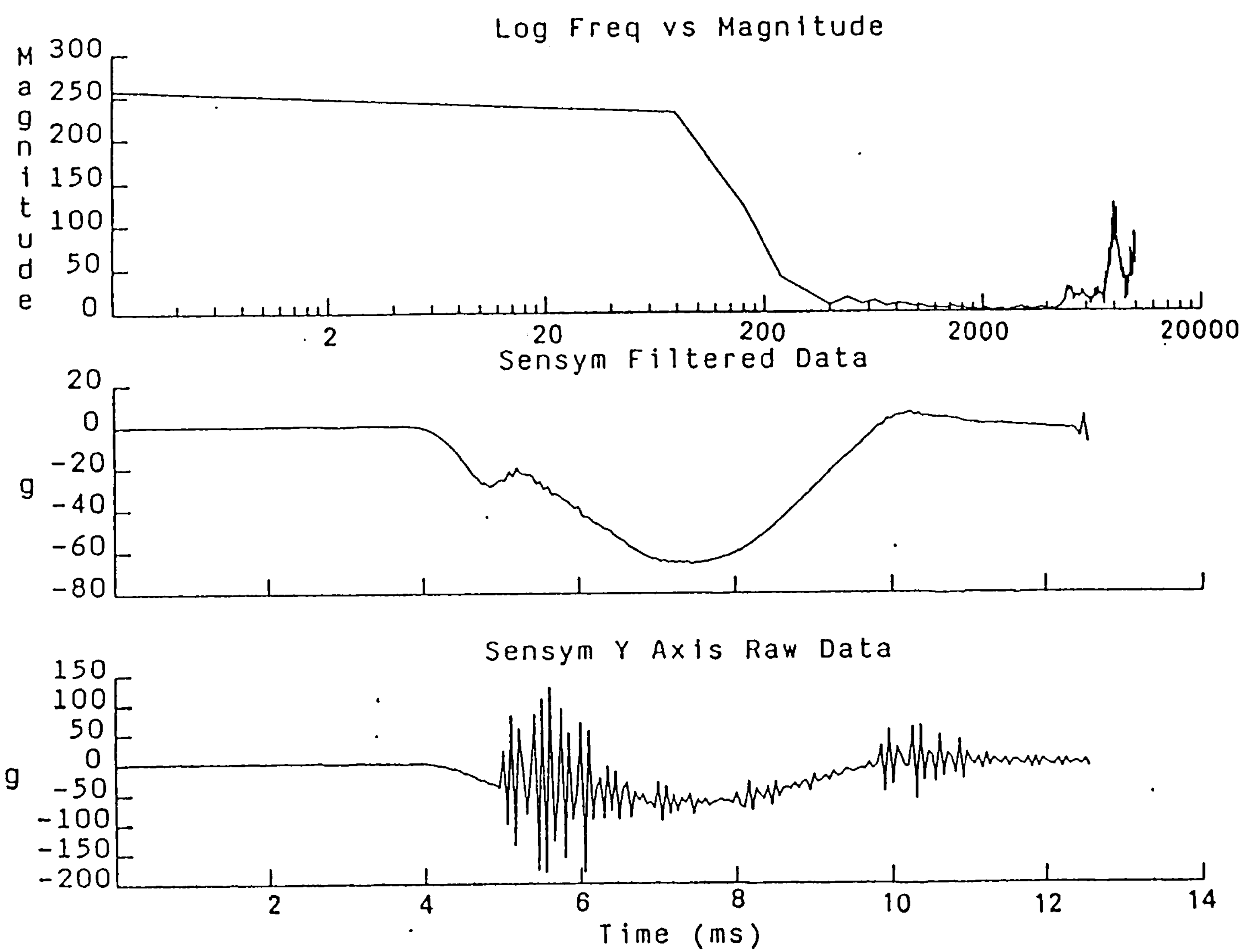

Figure 8b. Glass impact, solid state accelerometer response.

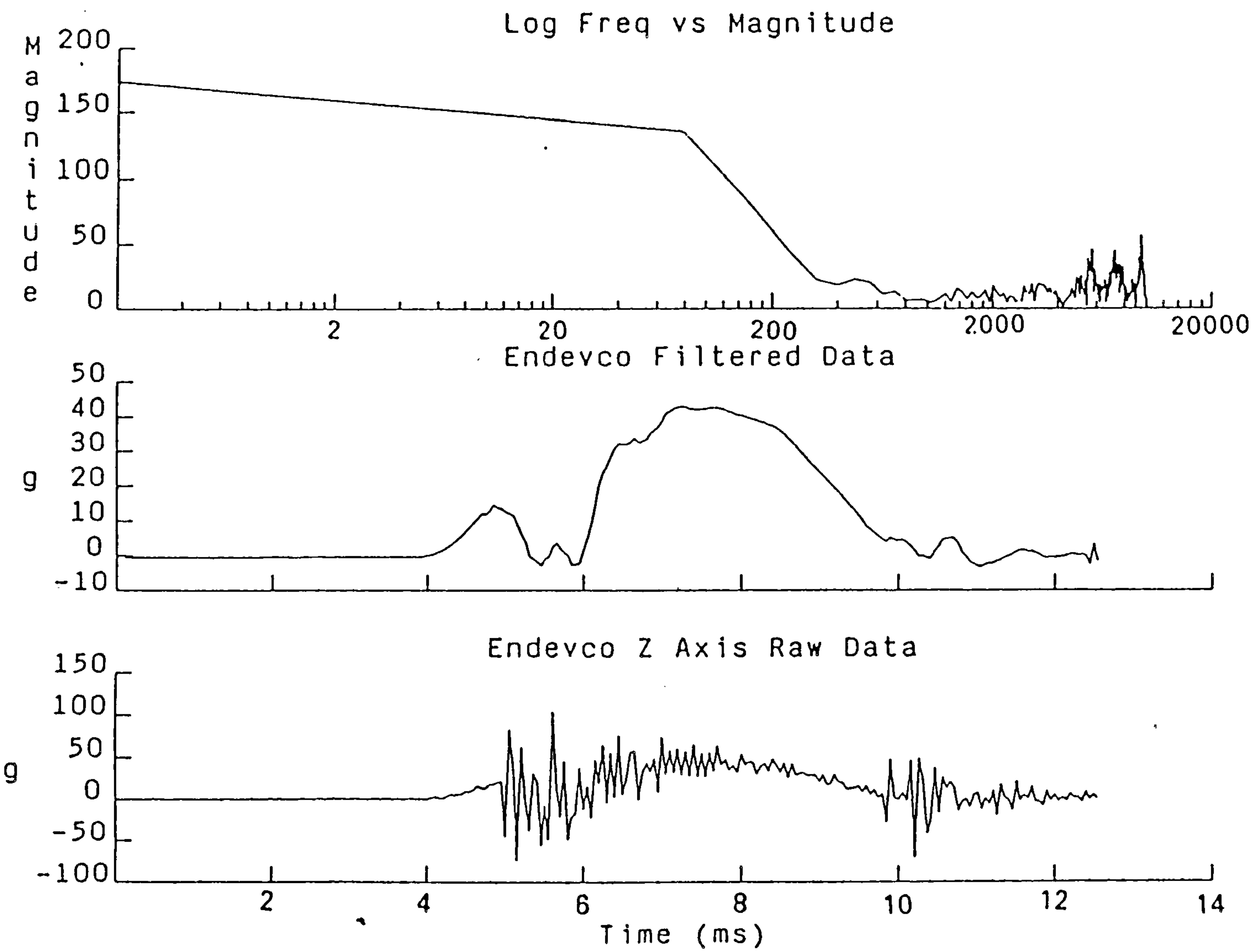

Figure 9a. Glass impact, conventional accelerometer response.

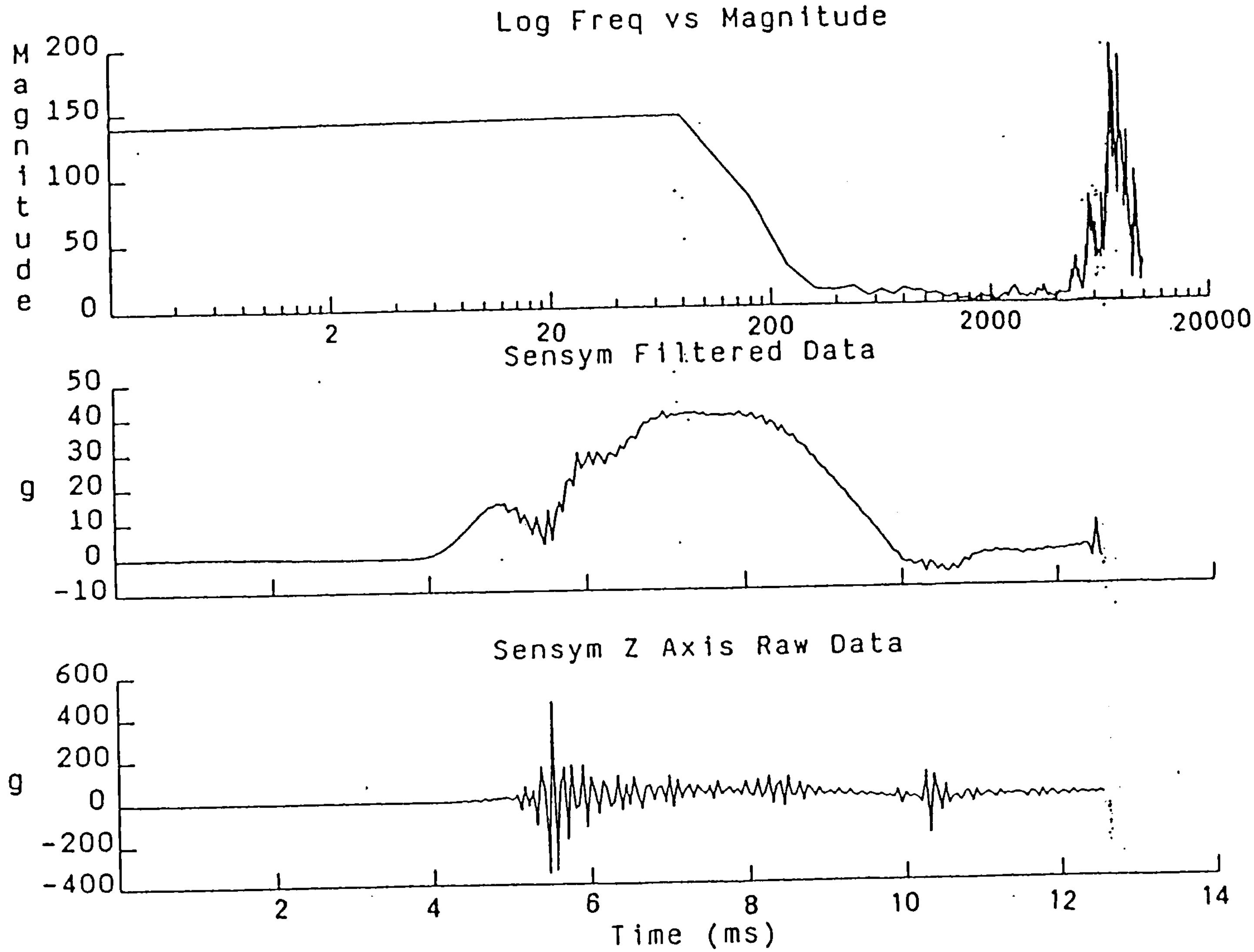

Figure 9b. Glass impact, solid state accelerometer response.

DISCUSSION

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SPEAKER: Joseph McCleary, General Motors Research Labs

QUESTION: Guy Nusholtz, Chrysler Motors Corp.

From the data you showed, it looked like the cross axis sensitivity was about 2%, is that correct?

ANSWER: Joe McCleary

It's hard to tell, because the shaker is not constrained in a lateral direction so the only thing that could be done is to compare it to the conventional accelerometer that did have a stated accuracy of 1%. Using that as a comparison, it was similar. We didn't have a real lateral fixture to simulate that cross axis.

Q. Could you comment on the longevity of these accelerometers?

A. We've used these in various tasks for about six to nine months and the only failure we had was due to an over voltage.